24 Holocene Sediment Erosion in Britain as Calculated from Lake-basin Studies

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INTRODUCTION

Myers (1993) estimated that, globally, approximately 75 billion tonnes of soil are eroded annually, the majority of which come from the world's croplands. Thus, each decade the global soil budget is being depleted by *c.* 7 percent (Walling, 1988). According to Pimental (1976), in the past two centuries the US has lost one-third of its topsoil. As a consequence roughly 80 percent of the world's agricultural land is deemed to be suffering from 'moderate to severe erosion' and a further 10 percent from 'slight to moderate erosion' (Speth, 1994). The variation in rates of erosion across the world is huge. Fournier (1960) reported that with average erosion rates of 1000–2000 t km^{-2} $year^{-1}$, losses in Asia, Africa and South America are greatest; losses are lowest in the US and Europe where the average yield is *c.* 0–600 t km^{-2} $year^{-1}$. These losses from predominantly agricultural areas contrast with those associated with undisturbed forests which range from only 0.4 to 5 t km^{-2} $year^{-1}$ (Bennett, 1939). A number of authors have attempted to calculate the financial implications of erosion in terms of both on- and off-site costs. Brown (1948) estimated that the impacts of sediment erosion downstream in the US cost in the region of $175 million annually, and Walling (1988) translates this into a 1988 value of *c.* $1000 million. Pimentel *et al.* (1995) suggested that, whilst the resulting decline in soil fertility in the US costs approximately $27 billion, the off-site environmental impact equates to an additional $17 billion (1992 dollars) a year. Thus he suggested that, in the US, the annual cost of sediment erosion resulting from agriculture is in the region of $44 billion per year, equivalent to about $100 per hectare of pastureland and cropland.

In Britain, quantitative estimates of erosion rates remain poor, particularly from an historical perspective. As reported by Moore and Newson (1986), long records of erosion are unusual in Britain. Consequently relatively little information on long-term erosion rates in British catchments is available. Work has tended to consider the relatively recent time period, particularly the past two centuries. This British work covers many important changes, including variations in erosion associated with shifts

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ı agricultural and forestry practices, and urbanisation. However, other fundamental hanges concerning historical land-use patterns and other human activities have been ırgely undocumented.

Here we use a catchment-based approach to study erosion. Sediment yield and flux stimates have been obtained from either reservoir re-survey data or lake sediment ıulti-core studies. Multiplying the sediment yield by a sediment-delivery ratio enables n erosion rate to be obtained. However, such experimental approaches are both me-consuming and expensive to undertake. It is thus desirable to predict sediment ux using a simple model. At present, sediment erosion models range from (i) simple elationships between sediment yield and a single physical catchment characteristic, g. the catchment to lake ratio (Dearing and Foster, 1993); through (ii) empirical quations relating the rate of erosion to a range of physical characteristics, e.g. the niversal Soil Loss Equation (USLE) of Wischmeier and Smith (1978); to (iii) highly etailed and complex models. At the moment all have their disadvantages. We discuss ie development of simple regression models which link catchment characteristics to diment flux within British lake catchments.

ODELS OF SEDIMENT EROSION

nking Sediment Accumulation to Sediment Yield

s a starting point, the equation

$$Y = M/A \tag{24.1}$$

n be employed to determine sediment yield in lake catchments. Here Y is the diment yield (t km^{-2} year^{-1}), M is the mass of material deposited in the basin ınually (t year^{-1}) and A is the catchment area (km^{2}). However, as Walling (1983, 88) has emphasised, sediment yield determined from lake sediment-based studies ɔes not take account of the deposition of material during transport, *en route* from urce to sink, whether it be in river channel or overland within the catchment. diment yield is therefore a function not only of the rate of soil loss but also of the iciency with which it is delivered (Jackson *et al.*, 1986). Thus in order to relate diment yield to erosion the sediment-delivery ratio, D, is an essential factor that ıst be considered. Haan *et al.* (1994) define the sediment-delivery ratio as

$$D = G/(Y \cdot A) \tag{24.2}$$

ıere G is the gross erosion occurring in the catchment per year (t year^{-1}). Sediment eld in lake catchments therefore becomes

$$Y = (M \cdot D)/A \tag{24.3}$$

ıere are a variety of difficulties in selecting a sediment-delivery ratio, D, for a given tchment as there are a range of factors that can influence it. Indeed Haan *et al.* 994: 293) state that, 'It should be pointed out that the degree of understanding of liment-delivery ratios is probably less than any other area of sedimentation.' evertheless a number of researchers have attempted to quantify the significance of

the various processes involved. Vanoni (1975) suggests that in basins larger than 1 km^2, often less than 25 percent of the material eroded reaches a given point downstream, whilst theoretical work undertaken by Trimble (1981) suggests that, in fact, sediment delivery may fall to a mere 6 percent. The American Society of Civil Engineering (ASCE, 1975) have adopted the empirical relationship

$$D = 0.36A^{-0.2} \tag{24.4}$$

between delivery ratio, D, and drainage basin area, A. Sediment delivery is seen to vary from more than 90 percent in some small catchments to less than 10 percent in the largest catchments. The general decrease in sediment-delivery ratio with catchment size is often attributed to a 'headwater' effect. Small lake or reservoir catchments tend to lie in the upper reaches of river systems where slopes tend to be steeper and erosion tends to predominate over deposition. Larger lake and reservoir catchments, in contrast, tend to lie in the lower reaches of river systems, with gentler slopes and more extensive floodplains which provide more scope for sediment retention.

Relationships between Sediment Yield and Catchment Characteristics

On a global scale, links between sediment yield and a number of physical parameters, such as catchment area and relief, have been investigated for various regions of the world. On the basis of discharge and sediment data for 60 large catchments, Strakhov (1967) produced a map illustrating the global pattern of erosion. He found that in large basins variations in suspended sediment yield of between 1 m^{3}km^{-2}year^{-1} and 4000 m^{3}km^{-2}year^{-1} and dissolved sediment yield of between 1 m^{3}km^{-2}year^{-1} and 450 m^{3}km^{-2}year^{-1} can be accounted for by physiography, soil type, vegetation cover and climate. Strakhov identifies two particular zones of erosion. First, a temperate moist belt in the northern hemisphere is broadly bounded to the south by the annual +10 °C isotherm. This zone is characterised by an annual precipitation of between 150 and 600 mm. It has low erosion rates, typically less than 10 t km^{-2}year^{-1}. His second zone includes parts of North America, South America, Africa and South East Asia. It corresponds to the area between the +10 °C isotherm in the northern hemisphere and the +10 °C isotherm in the southern hemisphere. His second zone is characterised by an average annual precipitation of between 1200 and 1300 mm. Here erosion is high, typically between 50 and 100 t km^{-2}year^{-1}, though rising to values in excess of 1000 t km^{-2}year^{-1} in the Indus, Ganges and Brahmaputra basins. Britain, along with most of Europe, falls into Strakhov's low erosion zone.

Links between spatial scale and yield have been studied by many authors. An important early study is that of Brune (1950) who investigated sediment loads for a range of drainage basins in the Sangamon River Watershed, Illinois. He too noted that average rates of sediment production decreased with increasing drainage area. Following on from Brune's work, Flaxman and Hobba (1955) surveyed sedimentation in 38 stockponds in the Columbia River Basin. They observed that drainage basin area was one of the five main factors accounting for 80 percent of the variation in sediment accumulation in their stockponds. Langbein and Schumm (1958) employed American gauging-station data for 94 catchments, and reservoir sedimentation data for 163 catchments, to study the relationship between precipitation and erosion. They found that sediment yields reached a peak at the transition zone between desert shrub and grassland conditions. Much lower yields were characteristic of both particularly dry regions and more humid regions. Langbein and Schumm (1958) suggested that the low sediment yields in very dry regions could be explained by the low runoff resulting from precipitation levels of less than 300 mm year^{-1}. Schumm (1963) also noted the effect of the relief ratio (maximum basin relief/length) on sediment yield. He found that an exponential increase in annual sediment yield was caused by the relief ratio in drainage basins of area 2.6 km^2 and greater.

Amongst others, Dearing and Foster (1993) have postulated links between sediment yield and the ratio of catchment area to lake area. They plotted the relationship between catchment to lake ratio and sediment yield for 20 studies of erosion in different environments in the world (Figure 24.1) and proposed that the data can be divided into two groups. One group represents sites with recent maximum sediment yield under cultivation/moorland while the second group illustrates maximum sediment yields under forest. Both groups of sites display a decrease in sediment yield as catchment to lake ratio increases. Dearing and Foster (1993) proposed that the negative correlation could be explained by two factors: first, the increase in storage as catchment area increases, and secondly, the erosion pathways between slopes, channels and the lake increased in importance at a slower rate than catchment area. They went on to suggest that for sites where the catchment to lake ratio is less than 10, sediment is more likely to originate from slope or surface processes than from channel banks. In contrast, they proposed that in larger catchments, where the catchment to lake ratio is greater than 10, a channel network is supported and thus the significance of channels as a sediment source increases.

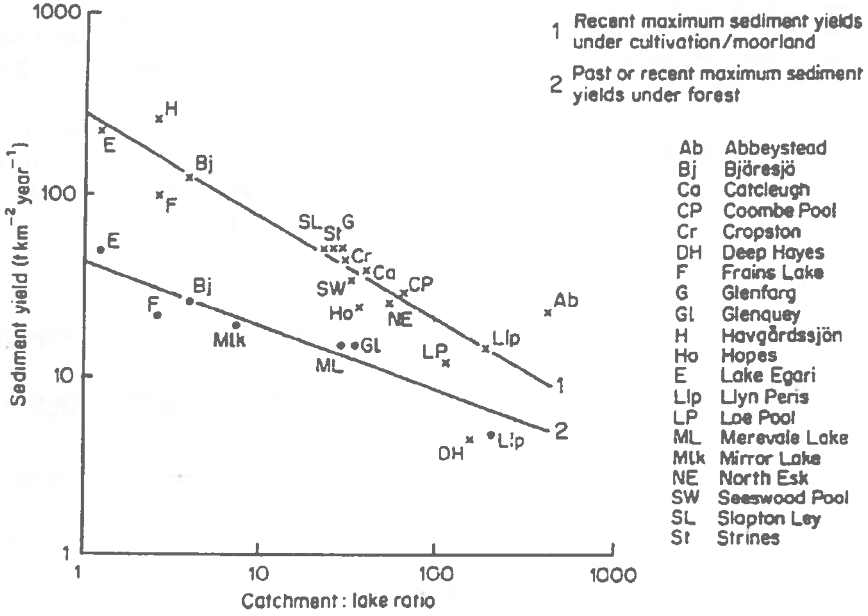


Figure 24.1 The relationship between catchment to lake ratio and sediment yield for 20 studies (from Dearing and Foster, 1993). Dearing and Foster (1993) have divided the data into two groups. The upper set comprises yield estimates obtained from catchments that are cultivated or are moorland. The lower set comprises sediment yield estimates from forested catchments

Modelling Sediment Yields and Processes

Following on from the work of Flaxman and Hobba (1955), Langbein and Schumm (1958) and Schumm (1963), more complex models of sediment yields and processes have been developed. Traditionally such models have tended to be based on empirical equations, though more recently much attention has been focused on what Foster (1990) terms 'process-based technology'. One empirical model is that of Fournier (1960). Using data from 78 drainage basins, Fournier derived the following equation:

$$\log Qs = 2.65 \log p^2/P + 0.46 (\log H)(\tan S) - 1.56 \qquad (24.5)$$

where Qs is mean annual sediment yield (g m^{-2}), p is the highest mean monthly precipitation (mm), P is mean annual precipitation (mm), H is mean catchment altitude (m), and S is the mean basin slope (degrees).

The Universal Soil Loss Equation

The most widely employed empirically based model is the Universal Soil Loss Equation (USLE). This well-known model was developed by Wischmeier and Smith (1978) from a database consisting of more than 10 000 plot-years of data. Plots studied ranged in length from 11 to 189 m and spanned a variety of soils, slope steepness, vegetation and climate in eastern North America. The model relates mean annual soil loss to rainfall erosivity, soil erodibility, slope length, slope steepness, a crop management factor and finally an erosion control practice factor. The USLE was designed for estimating inter-rill and rill erosion over time on small field plots. The equation was not designed to estimate soil loss for specific storm events. A number of authors have expressed concerns regarding the application of the USLE to larger areas (Meade, 1982). As noted by Foster (1982), the USLE is not designed to predict gully or channel bank erosion or to account for the deposition of material on hill slopes or channels, and hence assumes a sediment delivery ratio of one. Thus catchment studies which incorporate the USLE to estimate erosion need to add a sediment delivery term, D. Other limitations that have been identified in the USLE include the narrow database upon which it was built, i.e. American agricultural sites, along with theoretical problems, e.g. the lack of interaction terms.

As a result of the limitations posed by empirical models, efforts have been made towards the development of models that are better suited to predicting the distribution of sediment loss and runoff spatially on an individual storm basis as well as estimating total soil loss. Further improvements in erosion modelling are more likely to arise from models that incorporate key hydrological and erosion processes rather than from small developments based on the USLE. However, as noted by Rose *et al.* (1988, cited in Dickinson *et al.*, 1990), contemporary understanding of the processes surrounding the transport and detachment of soil remains inadequate and hence hampers efforts to obtain reliable input data and to validate models. The development of physically based models is still therefore at an early stage. Indeed Morgan (1995) reports that, in practical terms, estimates of erosion obtained from empirical models are often more reliable than those based on physical processes.

The Universal Soil Loss Equation combines catchment characteristics to estimate mean annual soil loss:

$$E = R.K.LS.C.P \tag{24.6}$$

where E is the mean annual soil loss in tonnes per hectare (t ha^{-1}), R is the rainfall erosion factor, K is the soil-erodibility factor, LS is the slope factor, C is the crop-management factor, and P is the erosion-control factor.

METHODOLOGY AND RESULTS

Sediment Flux in British Catchments

In order to investigate links between catchment/land-use characteristics and sediment flux within British catchments, a database has been compiled for 30 sites. At each of hese sites sediment-yield data are available from lake, or reservoir, sediment studies (Barlow, 1998). Mean sediment yields over a minimum time period of 50 years are vailable for each of these sites. In addition, 11 primary catchment and land-use haracteristics, plus seven derived characteristics, have now been determined (Barlow,

Table 24.1 Parameters employed in regression analysis and their potential influence on ediment flux

arameter	Relationship to sediment flux
ean annual precipitation	Soil loss closely related to rainfall through (i) detaching power when raindrops strike surface; (ii) rainfall contribution to runoff
aximum mean monthly precipitation	Employed to determine p^2/P
$^2/P$	Indicates concentration of rainfall in one month, measure of rainfall intensity
ake perimeter	Significance of lake bank erosion
atchment area	Area of potential erosion
og catchment area	Area of potential erosion. The log accounts for the effect of storage in larger catchments which results in a reduction in sediment yield with increasing area
ake area	Area of sediment deposition
atchment area: lake area ratio	Frequently plotted against sediment yield in the literature
iver lengths	Indicate significance of river bank erosion
ake altitude	Influence on rainfall and vegetation
ean catchment altitude	Influence on rainfall and vegetation. Perhaps related to slope gradient/catchment area?
oil erodibility	Resistance of soil to (i) detachment and (ii) transport
egetation	Soil protection offered by vegetation cover
lope gradient	Velocity of surface runoff
ength of slope	Volume of surface runoff
SLE sediment yield	Surface erosion, assuming no sediment storage
S	USLE combined slope length/gradient factor
	USLE rainfall erosivity factor

Table 24.2 Land-use and catchment characteristics determined for 30 catchments

Lake	National grid reference	Mean annual precipitation (mm)	Max. mean monthly precipitation (mm)	Lake perimeter (km)	Catchment area (km^2)	Lake area (km^2)	Stream length (km)	Slopes (%)	Lake altitude (m)	Average catchment altitude (m)	Catchment soil erosion susceptibility	Vegetation
North Esk Reservoir	NT155582	1077	116	1.8	7	0.10	16.0	14.7	340	462	2.12	0.010
Semer Water	SD918874	1375	161	2.4	43.6	0.26	96.6	7.5	248	532	27.05	0.012
Gormire	SE 505833	825	82	1.0	0.3	0.07	0.0	22.5	160	228	0.09	0.005
Glenfarg	NO16110	969	108	4.0	23.5	0.41	11.6	9.0	497	572	3.46	0.563
Loe Pool	SW648250	1032	125	6.0	55	0.44	47.6	4.1	5	99	19.86	0.394
R. Loch of Glenhead	NX450805	2360	267	1.2	1	0.125	1.6	19.6	300	370	0.22	0.010
Loch Valley	NX445817	2360	267	4.0	1.86	0.501	1.6	18.1	330	385	0.34	0.010
Loch Enoch	NX445851	2360	267	4.8	1.86	0.500	1.8	12.1	500	545	0.44	0.010
Merevale	SP300970	639	63	1.6	1.95	0.065	4.4	5.2	110	150	0.82	0.007
Llyn Geirionydd	SH605763	2555	329	2.8	3.90	0.26	6.0	10.4	190	479	1.71	0.007
Llyn Goddionduon	SH753586	2555	329	1.2	0.25	0.062	0.4	17.1	244	367	0.09	0.005
Seeswood	SP327905	639	63	1.6	2.21	0.067	4.0	2.0	125	145	0.93	0.379
Old Mill Reservoir	SX850522	1090	131	0.4	1.58	0.019	2.4	22.1	45	160	0.62	0.387
Kelly Reservoir	NS223685	1767	200	1.0	3.40	0.054	12.0	5.2	200	262	0.81	0.010
Llyn Peris	SH570620	2330	310	6.4	38	0.500	70.0	22.0	100	594	11.51	0.010
Lambieltham	NO502134	738	72	0.5	2.29	0.012	3.6	1.5	102	127	0.52	0.550
Harperleas	NO212053	949	93	1.8	3.44	0.162	6.8	9.8	259	360	0.52	0.010
Drumain	NO223043	949	93	0.4	1.53	0.020	2.6	4.4	231	278	0.24	0.010
Cullaloe	NT188875	796	82	3.6	4.13	0.162	4.0	6.8	89	144	0.85	0.552
Hornsea Mere	TA190447	652	66	2.8	16.70	1.200	12.0	2.4	0	13	8.61	0.384
Broomhead	SK260960	980	104	3.6	21.96	0.485	65.6	10.3	180	419	12.24	0.011
Chew	SE040020	1604	168	2.2	2.92	0.30	16.4	5.2	490	522	2.620	0.012
Deanhead	SE040415	1357	151	1.2	2.00	0.068	10.0	11.0	305	410	1.681	0.012
Gorple Upper	SE920315	1478	164	1.6	3.80	0.219	4.0	9.5	350	411	3.581	0.010
Gorpley	SE910230	1512	166	1.2	2.80	0.072	9.2	16.5	260	354	2.264	0.011
Ingbirchworth	SE215060	1006	109	1.6	7.72	0.217	4.4	5.3	260	308	3.301	0.017
Kinder	SK055883	1175	119	2.6	8.95	0.300	23.6	18.1	280	517	5.969	0.012
Mixenden	SE060290	1087	116	0.4	0.77	0.092	0.4	6.3	260	311	0.407	0.012
Snailsden	SE135040	1542	177	1.2	0.84	0.040	4.0	5.4	420	452	0.733	0.010
Widdop	SD930330	1326	144	2.4	8.90	0.039	4.4	15.2	320	408	7.399	0.010

98). Table 24.1 summarises these 18 parameters and their potential influence on diment flux. As shown in Table 24.2, the 30 catchments are characterised by a very oad range of land uses, soil types, altitudes, stream lengths and lake and catchment eas and thus are taken to constitute a representative cross-section of British sites.

ulti-core Studies of Sediment Yield

l 30 sites used in our study have been subjected to multiple-core studies or reservoir rveys. They provide records of sediment yield over long time periods, generally over least the past 100 years and often over thousands of years. Using average sediment elds over centennial time periods eliminates the short-term flux variability encoun-red in stream-monitoring estimates of sediment flux. At Loe Pool (O'Sullivan *et al.*, 82) exceptionally high sediment yields associated with intensive mining activity in e catchment in the period 1860–1938 are reported. For this one site the sediment eld used is for the shorter period 1938–1981, when agriculture was the dominant tchment activity.

Of the 30 sediment-yield estimates, 14 had been determined from reservoir re-rveys and 16 from multiple lake-sediment cores. The procedures used in the calcula-n of sediment yield at lake and reservoir sites are set out in Table 24.3. For lake or servoir sites where direct measurements of carbonate or biogenic silica content were t available, an average value, obtained from measurements made at other sites, has en applied to calculate the inorganic sediment flux. The flux and yield estimates m the multi-core studies for the 30 catchments are tabulated in Table 24.4. The an yield is 45 t km^{-2} year^{-1}, with a range of 1.8–260 t km^{-2} year^{-1}.

tchment Characteristics

even main characteristics have been determined for each of the 30 catchments. These catchment area, river length, catchment slope, altitude (lake and catchment), soil type (susceptibility to erosion), land use/vegetation, precipitation (mean and maximum), lake perimeter and lake area. Morgan (1995) gives a very comprehensive discussion of such catchment and land-use characteristics and describes alternative approaches to their estimation, while Barlow (1998) sets out in detail the methods used here to determine each of the 12 catchment characteristics.

ble 24.3 Twelve-step procedure for determining sediment yield using multi-core methods

p	Procedure
	Collect multiple cores
	Correlate cores
	Determine dry weights and dry densities
	Establish a chronology
	Determine the mean dry mass accumulation rate
	Multiply (5) by the area of active sedimentation
	Divide the total mass of material by the number of years in each time period to give a combined influx of allochthonous and authochthonous material
	Determine the average organic content
	Determine the carbonate content
	Determine the biogenic silica (diatom) component
	Subtract (8), (9) and (10) from the bulk influx. The result is the influx of minerogenic material per year
	Convert the influx into yield by dividing by the catchment area

Table 24.4 Sediment flux and catchment yields within the 30 catchments studied

Lake	Source of flux data[a]	Lake sediment yield (t km^{-2} year^{-1})	Lake sediment flux (t year^{-1})	USLE slope length factor	USLE sediment erosion (t km^{-2} year^{-1})	USLE erosion × catchment area (t year^{-1})	Sediment delivery ratio (SDR)	USLE erosion × SDR (t km^{-2} year^{-1})	USLE sediment flux (t year^{-1})
North Esk Reservoir	A	23.4	163.8	3.23	99.9	689	0.24	24.4	168.2
Semer Water	B	13.8	730.0	4.85	373.3	16182	0.17	63.1	2734.7
Gormire	B	44.6	8.7	2.14	94.6	27	0.44	42	11.8
Glenfarg	C	31.3	735.6	3.00	1348.2	31130	0.19	257.5	5945.9
Loe Pool	D	12.0	660.0	4.67	758.0	41358	0.16	122.8	6699.9
R. Loch of Glenhead	E	33.3	31.7	2.44	139.1	115	0.36	50.6	41.8
Loch Valley	E	66.1	122.7	2.19	118.4	161	0.32	37.6	51.0
Loch Enoch	E	89.4	166.3	2.42	117.4	160	0.32	37.3	50.8
Merevale	F	8.5	16.5	3.08	79.1	149	0.32	24.9	47.0
Llyn Geirionydd	G	12.5	48.7	3.10	137.1	499	0.27	37.6	136.7
Llyn Goddion duon	H	29.5	7.4	2.02	110.5	21	0.48	52.5	9.9
Seeswood	I	11.2	24.8	3.26	1071	2295	0.31	328.8	704.6
Old Mill Reservoir	J	69.0	109.0	2.61	1498	2338	0.33	492.8	769.3
Kelly Reservoir	K	36.9	125.5	3.41	71.8	240	0.28	20.3	67.8
Llyn Peris	L	10.6	402.8	4.12	250.9	9407	0.17	43.7	1636.8
Lambieltham	M	1.8	4.1	3.31	2721.5	6200	0.31	830.1	1890.9
Harperleas	M	11.5	39.6	3.17	42.0	138	0.28	11.8	38.6
Drumain	M	3.3	5.0	3.16	34.7	52	0.33	11.5	17.3
Cullaloe	M	26.2	108.2	2.82	2361.9	9372	0.27	640.1	2539.8
Hornsea Mere	B	42.0	770.0	2.61	4035.8	60537	0.21	827.3	12410.1
Broomhead	N	31.8	698.3	4.46	279.2	5996	0.19	54.2	1163.2
Chew	N	78.5	229.2	2.84	294.8	772	0.29	85.8	224.7
Deanhead	N	33.7	67.4	3.14	352.4	681	0.31	110.3	213.1
Gorple Upper	N	27.6	104.9	2.91	313.3	1122	0.28	86.5	309.7
Gorpley	N	129.1	361.5	2.66	355.1	969	0.29	104.0	283.8
Ingbirchworth	N	79.8	616.1	3.08	206.1	1546	0.24	49.3	369.5
Kinder	N	50.9	455.6	3.46	392.6	3396	0.23	91.1	787.9
Mixenden	N	9.5	7.3	2.68	180.3	122	0.38	68.3	46.3
Snailsden	N	260.2	218.6	2.83	242.1	194	0.37	90.3	72.3
Widdop	N	81.1	721.8	2.78	328.7	2912	0.23	76.6	678.5

[a] Source of sediment yield/flux estimates: A, Lovell *et al.* (1973); B, Barlow (1998); C, McManus and Duck (1985); D, O'Sullivan *et al.* (1982); E, Flower *et al.* (1987); F, Foster *et al.* (1985); G, Snowball and Thompson (1992) and Dearing (1992); H, Bloemendal (1982); I, Foster *et al.* (1986); J, Foster and Walling (1994); K, Ledger *et al.* (1980); L, Dearing *et al.* (1981); M, Duck and McManus (1987); N, Butcher *et al.* (1993).

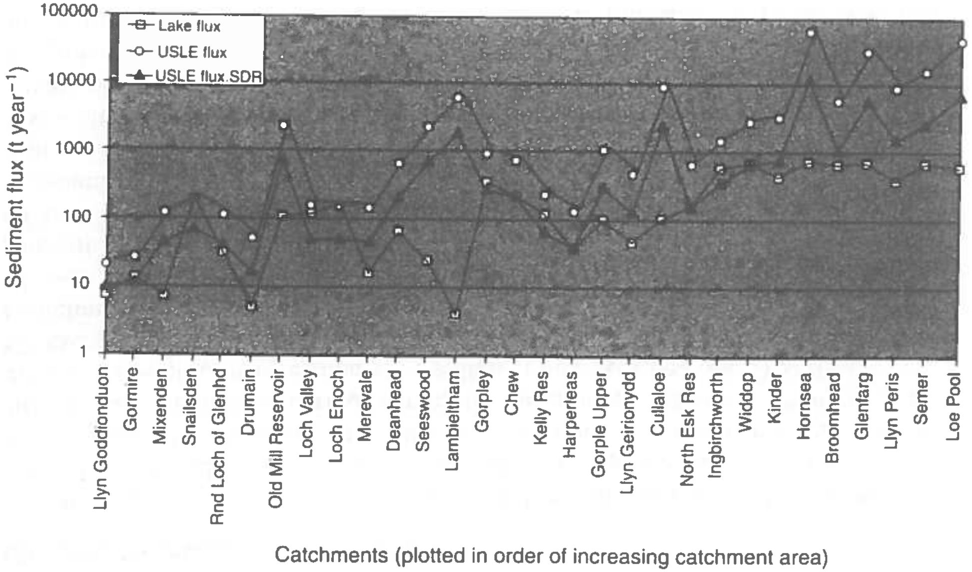
MODELLING YIELD AND FLUX IN BRITISH CATCHMENTS

Finding a relationship between sediment deposition in a lake and catchment erosion is not straightforward. Empirical relationships found by earlier workers between (i) catchment area and lake deposition, or between (ii) sediment yield and the ratio catchment area: lake area are not entirely satisfactory. Hence a more quantitative approach is sought, employing a statistical approach that uses catchment characteristics to improve, or modify in some way, the empirical relationships of earlier workers such as Brune (1950), Fournier (1960) and Dearing and Foster (1993).

USLE and sediment flux in British catchments

The results of our USLE calculations for the British catchments are set out in the final column of Table 24.4 for a standard slope, 22 m long. The average estimated soil loss at our 30 sites is 310 t km^{-2} year^{-1}. Figure 24.2 illustrates predicted sediment flux for each of the 30 catchments studied using (i) the Universal Soil Loss Equation alone and (ii) the Universal Soil Loss Equation estimate multiplied by a sediment-delivery ratio derived from the ASCE (1975) empirical relationship of equation (24.4). Figure 24.2 also compares sediment fluxes predicted using the USLE with our flux estimates based on the multi-core studies.

The USLE estimates of sediment flux are, with two exceptions (Snailsden and Loch Enoch), considerably greater than the multi-core flux estimates. The differences between the USLE and multi-core estimates of sediment flux can be largely attributed to the effect of sediment storage in catchments. Modifying the USLE sediment flux estimates by a sediment-delivery term makes the USLE flux estimates more comparable with those determined from the multi-core studies. Nevertheless at some sites, particularly the seven largest catchments in the database, there is considerable disagreement between the yield estimates obtained from lake sediments and those predicted using the Universal Soil Loss Equation. The discrepancy between USLE predicted sediment flux and lake sediment flux at Lambieltham is particularly marked. Duck and McManus (1987) suggest that the low sediment yield from the Lambieltham catchment results from reservoir management practices. A bypass channel has prevented water and sediment reaching the reservoir.



igure 24.2 A comparison of sediment flux to 30 British lakes/reservoirs using (i) the USLE one, (ii) the USLE multiplied by the US Soil Conservation Service sediment delivery ratio, and ii) the lake/reservoir estimates of sediment flux. The lake sediment flux estimates are generally wer than those obtained using the USLE multiplied by the US Soil Conservation Service sedi- ent delivery ratio. The lake sediment fluxes have been calculated on the assumption of 100 per- ent lake/reservoir trap efficiency

Regression Models of Sediment Flux

In an attempt to predict sediment flux into British lakes and reservoirs more accurately regression techniques have been employed to construct simple empirical models relating sediment flux to catchment and land-use characteristics. Table 24.5 lists the correlation coefficients between flux and yield with the 12 catchment characteristics. As would be expected, flux and catchment area have a significant positive correlation. Figure 24.3 demonstrates this relationship between sediment flux and catchment. However, the relationship

$$\text{Flux} = 18.5(\text{Catchment area}) \tag{24.7}$$

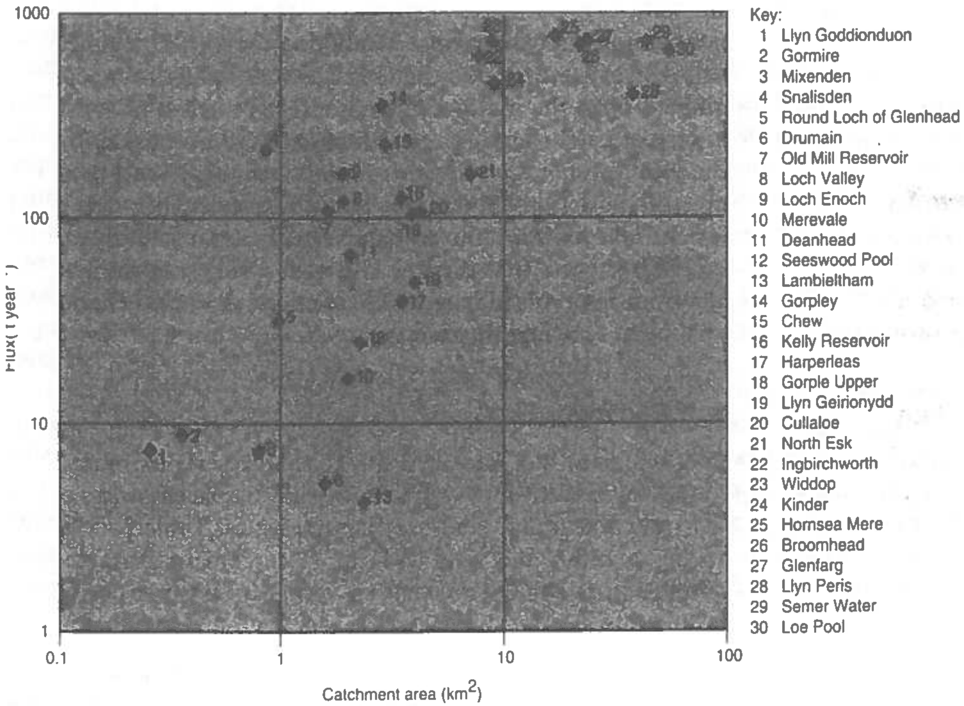
is rather weak, having an R^2 of only 0.52 and so is only a poor model of flux. In equation (24.7) the coefficient is the average yield, namely 18.5 t km^{-2} year^{-1}. In Table 24.5 we can also see that yield correlates weakly with altitude (both lake and catchment). Yield is also seen to be inversely correlated with catchment area for our 30 catchments, as found by Dearing and Foster (1993) and also by many earlier studies that have reported decreases in sediment yield with increasing catchment area.

In order to try to improve the flux model, stepwise regression analysis of all 12 land-use and catchment characteristics, plus the four parameters derived from them for inclusion in the Universal Soil Loss Equation, has been performed. Stepwise regression analysis uses the F-statistic to determine whether any particular variable should be included in the equation. By adopting the usual F-value of 4, this variable selection form of regression analysis generated the following equation:

Table 24.5 Correlation coefficients between sediment flux and the 12 catchment and land-use characteristics of the 30 catchments studied

	Catchment characteristics											
	1	2	3	4	5	6	7	8	9	10	11	12
Sediment flux	−0.19	−0.16	0.50	0.71	0.73	0.57	0.58	−0.09	−0.01	0.17	0.16	0.20
Sediment yield	0.17	0.13	−0.10	−0.24	−0.17	−0.07	−0.21	0.09	0.42	0.21	−0.20	0.30

1 Mean annual ppt; 2 Max. mean monthly; 3 Lake perimeter; 4 Catchment area; 5 Log catchment area; 6 Lake area; 7 Stream length; 8 Slope steepness; 9 Lake altitude; 10 Catchment altitude; 11 Vegetation; 12 Soil erodibility



igure 24.3 The relationship between sediment flux and catchment area for 30 British sites. n increase in sediment flux with increasing catchment area can be observed. However, the lationship has an R^2 value of only 52 percent and is thus relatively weak

$$\text{Flux} = -54.6 + 11.7\ \text{Catchment area} + 347\ \text{Lake area} + 264\ \text{Soil erodibility} \quad (24.8)$$

he relationship has an improved R^2 of 0.64 and a correlation coefficient of 0.8. In a rther attempt to improve on the simple relationship between catchment area and diment flux of equation (24.5) (Figure 24.3), and to account for the progressive crease in sediment storage as the catchment area increases, we have regressed the log f catchment area and sediment flux. The relationship between the log of catchment rea and sediment flux (Table 24.6) is significantly stronger than that observed etween catchment area and sediment flux, with an R^2 of 0.66 and a correlation oefficient of 0.81. It takes the following form:

$$\text{Flux} = 42.2 + 378 \log(\text{Catchment area}) \quad (24.9)$$

able 24.6 Summary of the R^2 values and correlation coefficients obtained using various ombinations of catchment characteristics to determine sediment flux

2	Correlation coefficient	Variables
75	0.87	Log catchment area, soil erodibility factor, USLE erosion rate
66	0.81	Log catchment area
64	0.8	Catchment area, lake area, soil erodibility factor
52	0.71	Catchment area

Indeed when the log of catchment area is added to the stepwise regression analysis, the log of catchment area is the only variable to be selected.

If the F-value is reduced to 3 then fewer parameters are removed from the full regression model during variable selection and the following regression equation is produced:

$$\begin{aligned}\text{Flux} = {} & 67.0 + 298 \log(\text{Catchment area}) + 243\ (\text{Soil erodibility}) \\ & + 0.0057\ (\text{USLE erosion rate})\end{aligned} \quad (24.10)$$

This relationship has an R^2 of 0.75 and a correlation coefficient of 0.87 (Table 24.6). However, it must be remembered that such a low F-value can lead to over-fitting.

Table 24.6 summarises the R^2 and correlation coefficients that result from employing various combinations of catchment characteristics to determine sediment flux. All the correlation coefficients and relationships of Table 24.6 are highly significant with p-values below 0.01. In selecting the most appropriate of these competing regression equations to estimate sediment fluxes, a balance between a strong correlation and a simple empirical model should be sought. With a larger data set the formal technique of cross-validation could be used to assess the number of variables to include in the model. The simple regression relationship employing the log of catchment area alone is seen to provide a reasonable account of sediment flux.

Power-law Relationships and Flux

An improvement on using the log of catchment area could be the use of power-law relationships of the type used in equation (24.4), e.g. flux = yield × area^n. The simplest power-law relationship found for the British sites is plotted in Figure 24.4. More involved power-law relationships were explored to try to improve on the fit of Figure 24.4. However, the results were very similar to those of the regression work. The power-law models consistently selected catchment area as the main predictor, with slope as an additional parameter. Once again, neither climatic factors nor the USLE yield estimates were found to be significant variables.

In summary, simple regression models involving catchment area, lake area and possibly soil erodibility can explain up to 66 percent of the variance of the flux at the 30 British sites analysed. By far the most dominant of these variables is catchment area. This parameter alone explains over 50 percent of the variance. Following Brune (1950), Boyce (1975), Walling (1983, 1988) and many others, we attribute the strong relationship between catchment area and flux to the role of sediment delivery in modulating sediment fluxes within catchments.

DISCUSSION

The Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) is the most widely used soil-erosion model available, and remains one of the simplest to use. However, this study has illustrated that estimates of sediment erosion determined for British catchments using the USLE

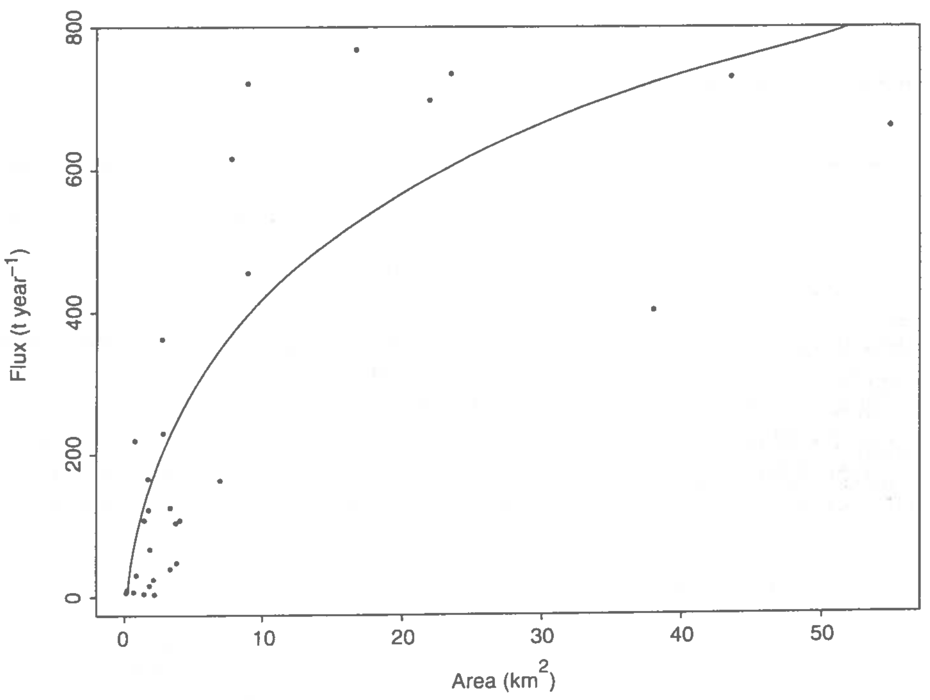


Figure 24.4 Power-law relationship between sediment flux and catchment area for the 30 British sites of Figure 24.3

tend to be considerably greater than those from the multi-core studies. The USLE only estimates surface-sheet erosion; it does not include gully or channel erosion and consequently it might be expected to underestimate erosion. One of the major limitations of the USLE is that it was designed for small plot studies rather than lake catchments. Consequently the slope-length factor was not designed to accommodate the downhill slope-lengths observed in catchments. Indeed Hickey *et al.* (1994) state that 'the largest problem in using the, USLE' has been the calculation of the cumulative downhill slope-length factor.

In other parts of the world a variety of studies employing the USLE to estimate soil erosion have similarly found that the USLE-determined erosion rates are higher than those obtained using other techniques. For example, Busacca *et al.* (1993) compared estimates of erosion in an agricultural watershed in Idaho, USA, using the Revised Universal Soil Loss Equation (RUSLE) with estimates determined using ^{137}Cs as a sediment tracer. They found that the RUSLE significantly overestimated erosion. Similarly, Harden (1993), working on an agricultural drainage basin in Andean Ecuador, noted that upland soil-erosion estimates determined using the USLE were consistently higher than estimates extrapolated from rainfall-stimulation experiments. Kusumandari and Mitchell (1997) compared rates of erosion determined using the USLE with those determined using the Agricultural Non-Point Source Pollution (AGNPS) model in a forested basin in West Java, Indonesia. The rate of erosion determined using the AGNPS model was found to be about half that predicted by the USLE. Taken together, all these results suggest that rates of erosion predicted using the USLE in UK catchments may be too high. However, from our compilations it is difficult to ascertain whether such high USLE flux estimates result from (i) overestimates of sediment erosion obtained using the USLE, or from (ii) underestimates of the sediment-delivery ratio.

A Sediment-Delivery Model

Sediment delivery remains an extremely complex and limiting factor in relating lake-sediment fluxes to erosion rates in catchments. Whilst lake-sediment flux estimates are an ideal way of determining the mass of material reaching a given point, insufficient data on rates of erosion in British catchments prevent the determination of more accurate estimates of sediment delivery. Consequently any attempts to develop our understanding of the factors that influence the delivery ratio, and quantify the importance of different factors, are limited. Simple sediment-delivery models, which can be more readily and easily applied to catchments, are very desirable. Such models enable the identification of catchments where further, more detailed, studies may be warranted in order to test hypotheses relating, for example, sediment delivery to slope-lengths or gradients. Our models indicate that the log of catchment area is more strongly related to sediment flux than catchment area alone. The soil type within a catchment also has a significant impact on its tendency to erode on Holocene timescales.

Sediment-Delivery Ratios in the Larger Catchments

The quantitative nature of our physically based models of Table 24.6 can be used to highlight an important point that has not been elaborated in previous studies. This concerns the larger British catchments such as that of Semer Water. Our models can be used to estimate theoretical volumes of material stored in sediment sinks by transforming them into simple mass-balance relationships (using equations (24.3) and (24.4)). At Semer Water, for example, by combining our estimates of sediment-delivery ratio with the volume of sediment in the lake we estimate the volume of sediment stored within the catchment to be about 50 million cubic metres. This sediment volume is equivalent to a mean sediment thickness over the whole of the catchment of 1.2 m. However, parts of the Semer Water catchment are characterised by slopes of steep gradient and although there are some areas where sediment accumulation may occur, it seems highly improbable that these are sufficient to result in a mean sediment thickness of >1 m over the entire catchment. Thus, either significant quantities of sediment are being lost through the lake outflow, or the sediment-delivery ratios underestimate the proportion of sediment entering the lake. Similarly, at Gormire, we estimate from our models that over one million cubic metres of sediment should remain in the catchment. However, at Gormire, steep slopes drain almost exclusively straight into the lake and thus there is again virtually no scope for sediment storage. Furthermore there is no outflow and so no scope for sediment loss. Thus we are left with the paradoxical situation that while the flux of sediments in

British catchments, and the variation of sediment-delivery ratio with catchment area, are in excellent agreement with other northern hemisphere studies, the volumes of sediment stored in the larger catchments appear to be too low to account for 'missing' sediment.

CONCLUSIONS

(1) In the United Kingdom monitored records of sediment yield covering time periods of more than a few years are rare.
(2) Sediment-flux estimates, based on multi-core studies, have here been assembled for 30 British lake catchments.
(3) The British sediment fluxes are similar to those found for other places in the temperate zone.
(4) Universal Soil Loss Equation estimates of sediment yield for the British catchments are higher than those of the multi-core studies.
5) A strong relationship ($R^2 = 0.75$) has been found between, on the one hand, sediment flux and, on the other, catchment area and soil-erosion susceptibility for the British catchments.
6) Multi-core studies of sediment accumulation in lakes/reservoirs confirm the view that small catchments (< 1 km^2) provide the best estimates of sediment yield (i.e. soil loss) because sediment-delivery ratios are close to one. Hence they provide a lower bound on sediment flux in Britain.
7) The apparently lower sediment yields of the larger catchments (> 10 km^2) can be reconciled with those of the smaller catchments by appealing to the relationship between catchment area and sediment-delivery ratio found in many parts of the world.
8) In mass-flux terms, a major imbalance is found, with millions of cubic metres of sediment apparently missing from large upland catchments.
9) Sediment-delivery ratio remains one of the most poorly understood and poorly quantified concepts in studies of sediment erosion.

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